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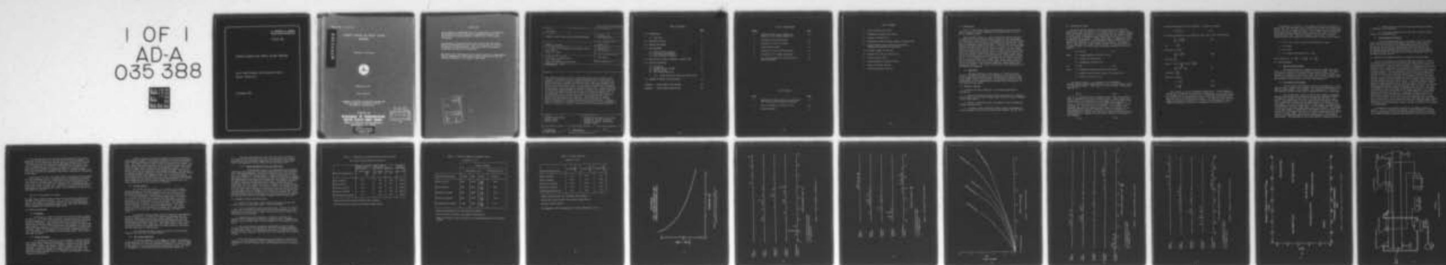

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# SYNTHETIC MOORING LINE TENSILE TESTING PROCEDURE

Coast Guard Research and Development Center
Groton, Connecticut

September 1975

Report No. CG-D-104-76



# SYNTHETIC MOORING LINE TENSILE TESTING PROCEDURE

Kenneth R. Bitting

September 1975

Final Report

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**DEPARTMENT OF TRANSPORTATION**
**UNITED STATES COAST GUARD**
**Office of Research and Development**
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16. Abstract

This report describes an effort to determine whether or not a tensile test procedure is necessary that will provide commonality among tensile tests of synthetic lines of all materials, diameters and lengths. A relationship was derived that relates material stiffness, diameter, and sample lengths to the strain rate during a tensile test. A first order experiment was conducted in which synthetic lines were tensile tested at various strain rates to determine to what degree tensile strength is affected by strain rate. Results show that the dispersion among individual data points overshadows the general trend of any strain rate effect and negates the need for a specific relationship. It is recommended that the strain rate be kept below 5 millistrains per second because the data points in that range are less disperse and the results derived from them should be more reliable. Some variation was observed between manufacturer's rated breaking strength and the test data. Although there are exceptions, a variation in strain rate generally has an insignificant effect on elongation at failure, spring constant and unit energy absorption.

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## LIST OF SYMBOLS

$A$ - Cross sectional area ($in^2$)

$C$ - Fundamental loading rate (lb/sec)

$F$ - Tension at failure (lb)

$K$ - Fundamental material spring constant ($lb/in/in/in^2$)

$k$ - Spring constant for a specific line material, diameter and construction (lb/in/in)

$\ell_o$ - Original length of line (in)

$\Delta\ell$ - Elongation of line at failure (in)

$T$ - Time to failure (sec)

$U$ - Energy absorbed at failure (in-lb)

$\varepsilon$ - Strain at failure (in/in)

$\upsilon$ - Cross head velocity (in/sec)

## 1.0 INTRODUCTION

The U. S. Coast Guard Research and Development Center has undertaken a program to develop lightweight mooring materials for use on aids-to-navigation buoys.

Synthetic-fiber lines (e.g. nylon, polyester) have been subjected to various field and laboratory tests in support of this development. The final step in these tests is a determination of the tensile strength. Test procedures were investigated to determine what tensile test conditions or procedures should be followed. A review of MIL STD and cordage industry procedures revealed that there is a variety of test procedures and that all are used for quality control purposes. The test sample length is generally short (about 5 feet) to reduce waste and the specified cross head speed (the moving part of the machine that applies the load to the sample) specified by different test methods varies widely. The same cross head speed is generally used for all materials and diameters. It was believed that it is possible that the tensile strength for one line could appear to be greater than another just by virtue of the test conditions. The need to investigate a relationship among synthetic line properties that provides commonality among tensile test results was apparent. This report derives such a test relationship and determines its usefulness.

### 1.1 Objectives

The major objective of this report is to derive and test a simple relationship of tensile test parameters that will allow the direct comparison of maximum tensile strength data of synthetic lines of any length, diameter and material. The secondary objective is the documentation of the experimentally determined physical properties of the synthetic lines tested.

## 2.0 TECHNICAL APPROACH

To achieve the above objectives, the following approach was implemented:

a. Derive a relationship among selected properties of a synthetic line to insure that the rate of energy input per unit volume is identical in all tensile tests.

b. Conduct a sensitivity test to determine if tensile strength is affected by strain rate.

c. If needed, conduct additional tensile tests to determine the tensile strength of each line at strain rates specified from (b) above.

## 3.0 TENSILE TEST THEORY

To insure that all synthetic lines are subject to the same test conditions so that the results can be compared directly, a simple first order relationship was derived. It is theorized that if energy is applied to a unit volume of material at a predetermined rate the tensile strength of all lines can be compared without concern that the data for one line is prejudiced by procedure. A simple relationship is sought that relates the physical properties of a line (diameter, length, stiffness) to the speed of the cross head of the tensile testing machine. A synthetic line is represented by a simple elastic spring. The energy absorbed in a sample is equal to the area under the tension-elongation curve and is equal to:

$$U = 1/2\ F\Delta\ell \qquad \text{(I)}$$

where $U$ = energy absorbed at failure (in-lb)

$F$ = tension at failure (lb)

$\Delta\ell$ = elongation at failure (in)

Let

$$F = KA\varepsilon \qquad \text{(II)}$$

where $K$ = fundamental spring constant ($lb/in/in/in^2$)

$A$ = original cross sectional area of line sample ($in^2$)

$\varepsilon$ = strain at failure (in/in)

The spring constant, k, is assumed to be a fundamental material property which is modified by the area to characterize a spring of a specific stiffness. This, however, is not the case. Rearranging Equation (II),

$$\frac{F}{A} = K\varepsilon \qquad \text{(IIA)}$$

where F/A is proportional to the maximum tensile stress of the material since it represents the stress at sample failure. Using tensile data obtained from a line manufacturer, the maximum tensile strength divided by the area (F/A) of the line is plotted against line diameter in Figure 1. The data shows F/A is not constant for all diameters of the same material. Since the strain at failure, $\varepsilon$, is constant at all diameters, Equation IIA indicates that K cannot be a constant for all line diameters of a material. Therefore, KA will be defined as a diameter/material property rather than just a material property and will be redefined as k. Equation IIA can then be rewritten for a specific line diameter

$$F = k\varepsilon \qquad \text{(III)}$$

Substituting Equation III into Equation I, Equation I becomes

$$U = \frac{1}{2} k\varepsilon\Delta\ell \qquad \text{(IA)}$$

The energy absorbed per unit volume per unit time is (for a fixed area):

$$\frac{U}{\ell_o T} = \frac{1}{2} \frac{k\varepsilon\Delta\ell}{\ell_o T} \qquad \text{(IV)}$$

Let $\varepsilon = \frac{\Delta\ell}{\ell_o}$

Equation IV becomes

$$\frac{U}{\ell_o T} = \frac{1}{2} \frac{k\varepsilon^2}{T} \qquad \text{(IVA)}$$

Since $\frac{\varepsilon}{T} = \frac{v}{\ell_o}$

where v = cross head velocity $(\frac{in}{sec})$

$$\frac{U}{\ell_o T} = \frac{1}{2} k\varepsilon \frac{v}{\ell_o} \qquad \text{(V)}$$

Letting $C = \frac{2U}{\ell_o T}$

Equation V becomes

$$C = k \frac{\varepsilon v}{\ell_o} \qquad \text{(VA)}$$

$$v = \frac{C\ell_o}{k\varepsilon} \qquad \text{(VI)}$$

The constant, C, is the fundamental loading rate. This fundamental loading rate is modified by the material properties k, $\varepsilon$, and $\ell_o$ to obtain the loading rate (v) for a specific line. Identifying and maintaining this rate insures that the energy input per unit volume per unit time is equal among all tests on lines of the same diameter. It should be noted that this simple relationship is restricted to lines of the same diameter. A more complete relationship is required to accommodate the variation in area.

To determine the constant C, the Cordage Institute Test Procedure is used so that this test method will coincide with at least one existing test method. The test procedure specifies a 5-foot sample and cross head speeds not greater than 12 inches per minute. Nylon plaited line is used because the Cordage Institute method covers plaited line and nylon is the most common synthetic line. Half-inch diameter line was used to provide continuity with other research at the R&D Center on lines of this diameter.

$k = 2.97 \times 10^4$ lb/in/in (Taken from manufacturer's data)

$v = 12$ in/min

$\ell_o = 60$ inches

$\varepsilon = .29$ (Taken from manufacturer's data)

Using Equation VI, $C = \frac{kv\varepsilon}{\ell_o} = 1722 \frac{\text{lb}}{\text{min}} = 28.7 \frac{\text{lb}}{\text{sec}}$

## 4.0 TEST EQUIPMENT

### 4.1 Tensile Testing Machine

The tensile tests were conducted using the tensile test capability of the cyclic/tensile test machine at the R&D Center. The tensile test machine consists of a hydraulic cylinder with a 155-inch travel mounted on a horizontal frame 48 feet long. The hydraulic cylinder speed can be varied between 10 and 60 inches per minute by a flow control valve. The specimen is enclosed with a wire cage (see Appendix 1).

### 4.2 Dual-Sheave Extensiometer

The dual-sheave extensiometer measures the elongation of a line sample during a tensile test by measuring the relative displacement of two ends of a gauge length on the specimen. The extensiometer is mounted on the hydraulic cylinder so that risk of damage during a test is minimized.

The extensiometer consists of two 10-inch diameter lightweight aluminum sheeves and a rotary variable differential transformer (RVDT). One sheave is attached to the rotor of the RVDT and the other to the stator. Fine monofilament lines are passed around the sheaves and lead over a combination of sheaves to the gauge length at the middle of the line sample. The lines are attached with small hooks to the specimen at points approximately five inches apart. As the specimen elongates during a tensile test, the entire gauge length moves and elongates. The movement of the gauge length is transferred by the filament line to the RVDT and results in a DC voltage output that is linearly proportional to the elongation of the gauge length. The strain at failure is then determined by dividing the elongation measured by the extensiometer by the original gauge length. The advantages of using this method of measuring strain are:

1. Actual strain in the line is measured without the effect of slippage in the termination.

2. Strain can be measured up to the time of failure without damage to the instrumentation.

### 4.3 Data Recording Techniques

The tension-elongation data is recorded on an X-Y plotter by connecting linear variable differential transformer (LVDT) type load cell to one plotter axis and the extensiometer output to the other. The data is also monitored on digital panel meters during the test. The maximum tensile strength and elongation are taken from the chart by applying the appropriate conversion factors. The energy absorption and spring constant are computed from the tension-elongation curve as discussed in later sections.

## 5.0 SENSITIVITY OF TENSILE STRENGTH TO VARIATIONS IN STRAIN RATE

Now that a theoretical relationship (Equation VA) has been derived that relates cross head speed to material and sample properties, it must be determined from tests if tensile strength is actually a function of cross head speed. Based on the test results, a determination can be made whether or not a relationship like Equation VA is required at all. To accomplish this a series of tensile tests were conducted at two different cross head speeds. The load elongation curve for each line sample was recorded during the test using the procedure and techniques outlined in Section 4.0. The tensile strength and elongation at failure are taken from the curves. Five-foot samples of nylon 8-strand plaited and 2-in-1 braided, polyester 8-strand plaited and 2-in-1 braided, and polypropylene 8-strand plaited line were tensile tested. Cross head speeds of approximately 10 inches per minute and 54 inches per minute were used. These speeds are approximately the upper and lower limit of speed of the tensile testing machine and they provide sufficient spread in tensile test data to determine if tensile strength is affected by strain rate. Ten inches per minutes is also in the range of the speeds specified in the Cordage Institute Procedure (Section 3.0). Cross head speeds of 10 inches per minute and 54 inches per minute are equivalent to strain rates of 2.7 millistrain per second ($10^{-3}$ in/in/sec) and 15 millistrain per second for a 5-foot sample. Strain rate is a more useful term than cross head speed because strain rate includes both cross head speed and sample length. Because it is a more general term and can relate to lengths greater than the commonly used 5-foot sample, strain rate will be used for the remainder of the discussion.

A histogram of the tensile strength of each sample is shown in Figure 2. The "o" represents the tensile strength obtained at a strain rate of approximately 2.7 millistrain per second and the "x" represents the tensile strength obtained at approximately 15 millistrain per second.

It is observed that, in all cases, the data points are quite dispersed and the data points for the two strain rates are overlapped. The dispersion of the points about the mode point is typically 10-15 percent. Since the strain rate was increased by approximately 450 percent (i.e., from 2.7 millistrain per second to 15 millistrain per second) and there is no pronounced variation in tensile strength, it is concluded that strain rate probably has an insignificant effect on tensile strength. To prove that conclusively, additional tests must be conducted at intermediate strain rates.

Since strain rate had a very small effect on maximum tensile strength, it is not necessary to use a relationship that is as complex as Equation VI. The data indicates that, in many cases, the tensile strength of the lines tested at the high strain rate show a greater dispersion of data points than at the low strain rate. Therefore, it is recommended that the strain rate during a tensile test (regardless of material) be kept below approximately 5 millistrains per second. The relationship governing cross head speed will then be:

$$\frac{v}{\ell_o} = \frac{\varepsilon}{T} < 5 \text{ millistrains per second}$$

For each type of sample tested, several very low tensile strengths were recorded at the high strain rate. If it is valid to extrapolate that trend to the right (i.e., greater strain rate), that would approach an impact load and might substantiate reports that some lines have failed at what appeared to be fairly low impact loads.

## 6.0 PHYSICAL PROPERTIES

### 6.1 Elongation

A histogram of strain at failure for the lines tested is shown in Figure 3. It is seen that, in general, the data points are dispersed and the elongation at 2.7 millistrains per second and 15 millistrains per second are overlapped. Test results indicate that strain rate has no significant effect on elongation except for nylon-braided line which does group together. Results also indicate that the elongation at failure may increase by approximately 15 percent if the strain rate is increased over the range tested. To determine the characteristic elongation for each line, all data points are combined and the average taken. These results are shown in Table 1.

### 6.2 Tensile Strength

As discussed in Section 5.0, the variation of tensile strength with strain rate is generally insignificant. However, the data does indiate slight trends: the tensile strength of nylon plaited and braided and polyester plaited line appear to decline slightly as strain rate increases. Polyester braided line shows an opposite trend while polypropylene plaited line appears to be unaffected by strain rate. The data for polyester braided line is so dispersed that meaningful observations are not possible.

Table 2 condenses the data and compares it with the advertised rated breaking strength. The plaited line meets or exceeds the advertised rated breaking strength and the double braided line is 14 and 21 percent lower. The "Range" column in Table 2 shows the spread of data points. The lowest tensile strength recorded for two of the three plaited lines tested was still higher than the advertised rated breaking strength. The lowest tensile strength value recorded for the braided lines was as much as 33 percent lower than the advertised rated breaking strength. The average of all tensile strengths regardless of strain rate is cited because the effect of increased strain rate is generally small and the increased number of data points would lend validity to the value. The mode and average tensile strength are very similar; the average tensile strength will be cited (even though the data does not display normal distribution) since that term is used widely in the field and in literature.

### 6.3 Spring Constant

The overall spring constant, k, is a ratio of the maximum tensile strength to the strain at failure. Its use implied a linear relationship between load and elongation which is not the case for most material/construction combinations, as can be seen from Figure 4. It is more meaningful to use the spring constant for the particular section of the curve that represents the load range of interest. The slope of the tension-strain curve for the material/construction combinations was calculated at the one-third point. (See Appendix 2.) Spring constants, $k_1$ and $k_2$, are the spring constants at the lower portion and upper portion of the curve, respectively. The overall spring constant, k, was calculated by dividing the tensile strength (from Table 1) by the strain. The spring constants are shown in Table 3.

An adjusted spring constant could be obtained by using Equation IV and solving for k. In effect, this procedure rearranged the area under the tension-strain curve into a right triangle of the same area. Therefore, the energy under the original tension-elongation curve and the adjusted curve would be the same. This would yield a linear stress-strain relationship and a constant k. This would, however, cause the calculated tension to be greater than the actual tension at low strains and less than actual at high strains.

The histogram in Figure 5 shows the range of overall spring constants that occur for the samples tested.

### 6.4 Unit Energy Absorption

The energy absorbed by a line sample at failure is determined by measuring the area under the tension-elongation curve. The unit length energy absorption is the energy absorption divided by the original length of the sample; it is the area under the tension-strain curve. The value is fundamental to each material/construction/diameter combination.

The unit energy absorption for each line is shown in Figure 6. It is observed that the effect of strain rate variation on unit energy absorption is not significant largely due to the spread of data points and the overlapping of the data points for the two strain rates.

### 6.4.1 Energy Absorption Efficiency Coefficient

It was desired to derive an energy absorption efficiency coefficient which typifies that inherent characteristic of each synthetic line. The energy absorbed at failure (U) divided by the strain at faillure ($\varepsilon$) indicates the relative amount of energy absorbed and the strain required to absorb it. The coefficient is useful in ranking the candidates, but caution must be exercised in selecting a material/construction combination based solely on the efficiency coefficient. For example, referring to Table 2, polyester braided line has the highest energy absorption coefficient, $U/\varepsilon$, but in absolute values, it absorbs less energy per unit length than any of the others. The values in Table 1 are plotted in Figure 7 to show the relative ranking of the materials based on several criteria. The table shows that, for example, nylon plaited line has the highest unit energy absorption ($U/\ell_o$), elongation ($\varepsilon$) and tensile strength (T). Polypropylene plaited line also has high unit energy absorption and elongation but only has 60 percent of the tensile strength of nylon plaited line.

## 7.0 SUMMARY OF RESULTS AND CONCLUSIONS

1. Results of the tensile tests conducted generally indicate that strain rate has no significant effect on tensile strength.

2. It is concluded that the strain rate during a tensile test should be kept below 5 millistrain per second because the data points are less dispersed in that range than at higher rates and the results derived from them should be more reliable.

3. Although there are exceptions, a variation in strain rate generally has an insignificant effect on tensile strength, elongation at failure, spring constant and unit energy absorption of the synthetic lines tests.

4. The rated breaking strengths as advertised by some line manufacturers were found to be substantially different from those determined by these tensile tests. The discrepancy may be due to experimental error such as splicing technique; sufficient data is not available for a definite finding.

5. While additional experimentation may be required to confirm the extension of these findings to lines of diameters other than 1/2", it is reasonable to conclude initially that these findings apply to all diameter lines.

Table 1. Comparison of energy absorption coefficient ($\frac{U}{\varepsilon}$) with other selected physical properties

| Material/Construction | Energy Absorption Coefficient $\frac{U}{\varepsilon}$ ($10^4$) $\frac{\text{in-lb}}{\frac{\text{in}}{\text{in}}}$ | Unit Energy Absorption $\frac{U}{l_o}$ $\frac{\text{in-lb}}{\text{in}}$ | Strain $\varepsilon_{ave}$ $\frac{\text{in}}{\text{in}}$ | Tensile Strength $F_{ave}$ (lb) |
|---|---|---|---|---|
| Nylon plaited[1] | 1.37 | 743 | .284 | 7878 |
| Nylon braided[2] | 1.30 | 526 | .211 | 6512 |
| Polyester plaited[1] | 1.33 | 467 | .184 | 6690 |
| Polyester braided[2] | 1.40 | 360 | .132 | 6400 |
| Polypropylene plaited[1] | 1.21 | 655 | .285 | 4980 |

[1]Eight-strand plaited line (Columbian Rope Company)

[2]Two-in-one double braided line (Samson Cordage Works)

Table 2. Tensile strengths of synthetic lines.

Diameter = 1/2"

| Material/Construction | Tensile Strength: Measurement (lb) Average | Tensile Strength: Measurement (lb) Mode | Tensile Strength: Measurement (lb) Range | Tensile Strength: [3]Advertised (lb) Average |
|---|---|---|---|---|
| Nylon plaited[1] | 7878 | 8000 | 7200<br>8800 | 6720 |
| Nylon braided[2] | 6225 | 6400 | 5500<br>7000 | 8300 |
| Polyester plaited[1] | 6690 | 6600 | 6100<br>7400 | 6720 |
| Polyester braided[2] | 6400 | 7000 | 5600<br>7000 | 7500 |
| Polypropylene plaited[1] | 4980 | 5000 | 4600<br>5200 | 4410 |

[1]Eight-strand plaited line (Columbian Rope Company)

[2]Two-in-one double braided line (Samson Cordage Works)

[3]Taken from technical data published by the above manufacturer of the lines tested

Table 3. Spring constants.

Diameter = 1/2"

| Material/Construction | $k_1(10^4)\ \frac{lb}{in/in}$ | $k_2(10^4)\ \frac{lb}{in/in}$ | [3] $k(10^4)\ \frac{lb}{in/in}$ |
|---|---|---|---|
| Nylon plaited[1] | 1.75 | 4.56 | 2.77 |
| Nylon braided[2] | 2.48 | 4.31 | 3.08 |
| Polyester plaited[1] | 2.58 | 5.06 | 3.63 |
| Polyester braided[2] | 3.98 | 6.64 | 4.92 |
| Polypropylene plaited[1] | 1.94 | 1.94 | 1.74 |

[1] Eight-strand plaited line (Columbian Rope Company)

[2] Two-in-one double braided line (Samson Cordage Works)

[3] Overall spring constant,

See Appendix 2 for an explanation of spring constants $k_1$, $k_2$, $k$.

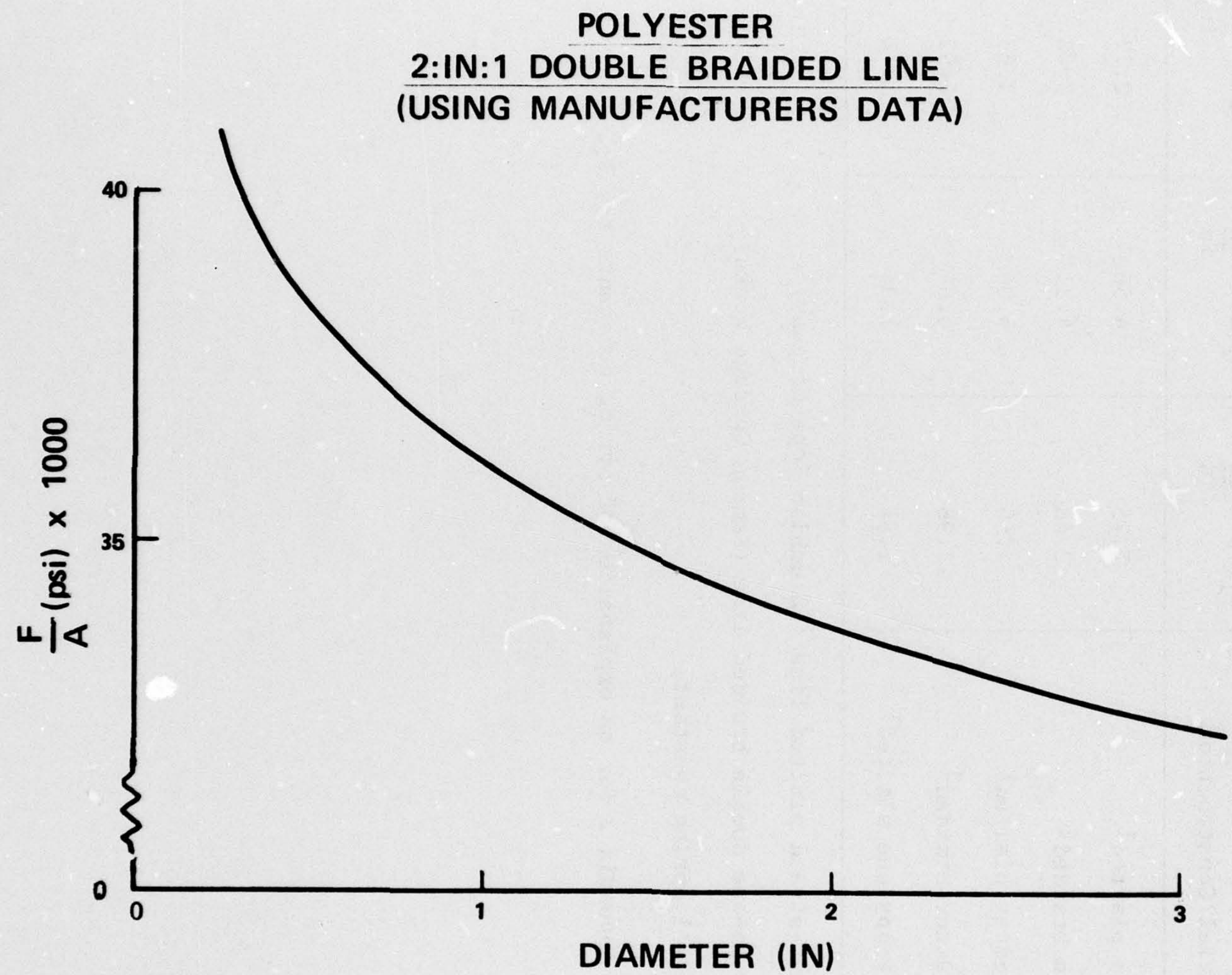
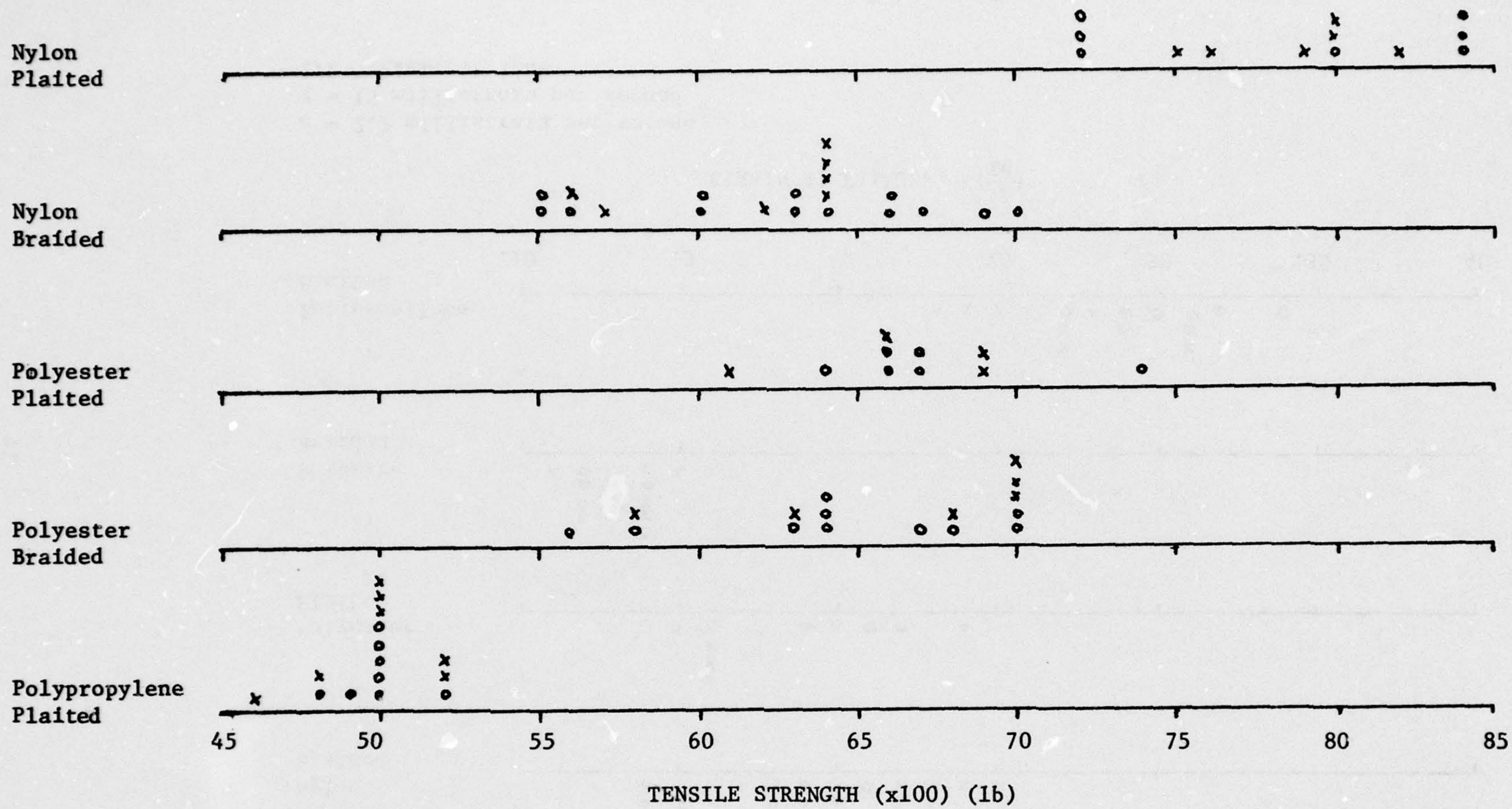
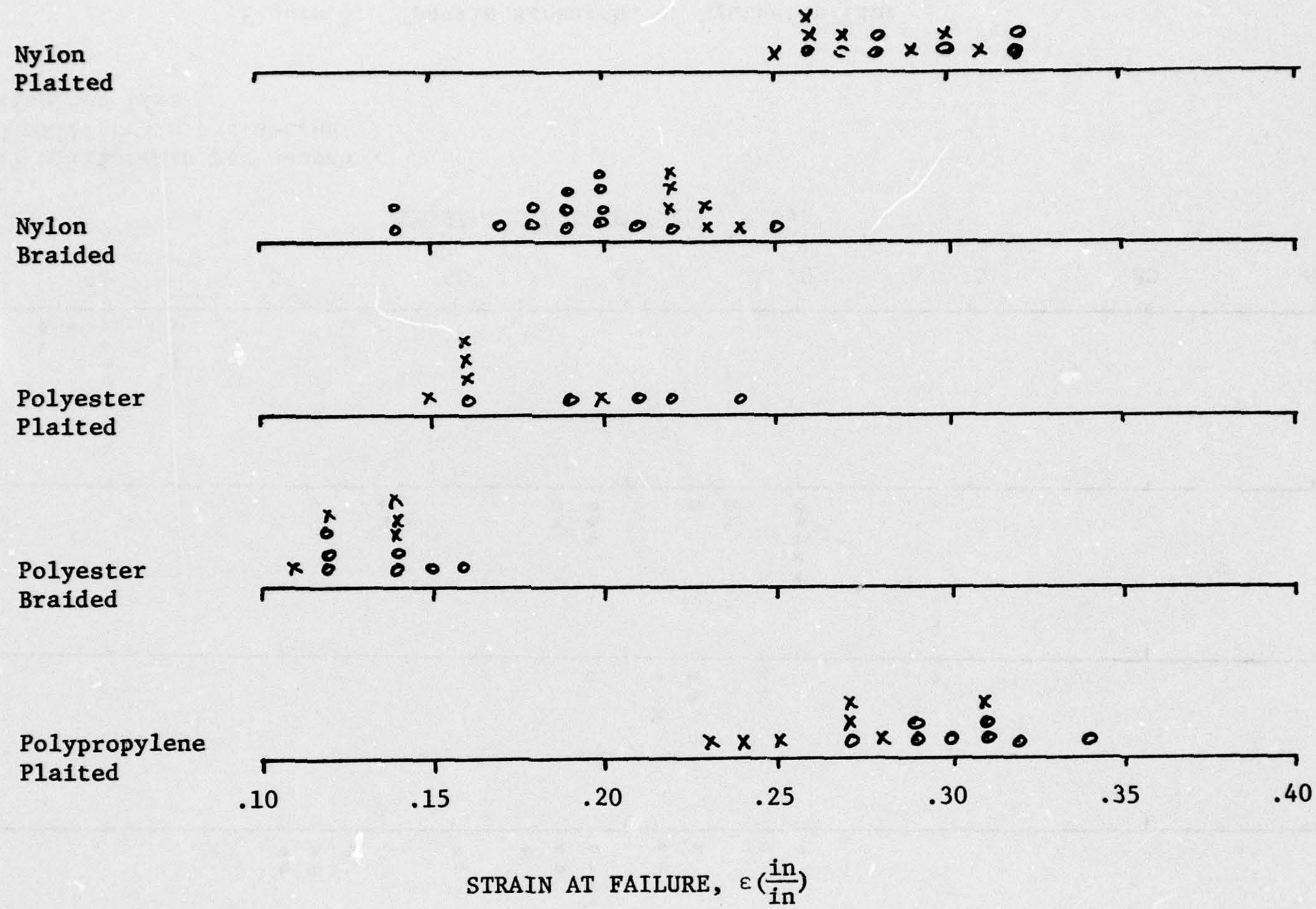



Figure 1. Tensile stress versus diameter of polyester 2-in-1 double braided line.




o = 2.7 millistrain per second
x = 15 millistrain per second
1/2" diameter line

Figure 2. Tensile Strengths of Synthetic Line




o = 2.7 millistrain per second
x = 15 millistrain per second
1/2 " diameter line

Figure 3. Histogram of Strain at Failure

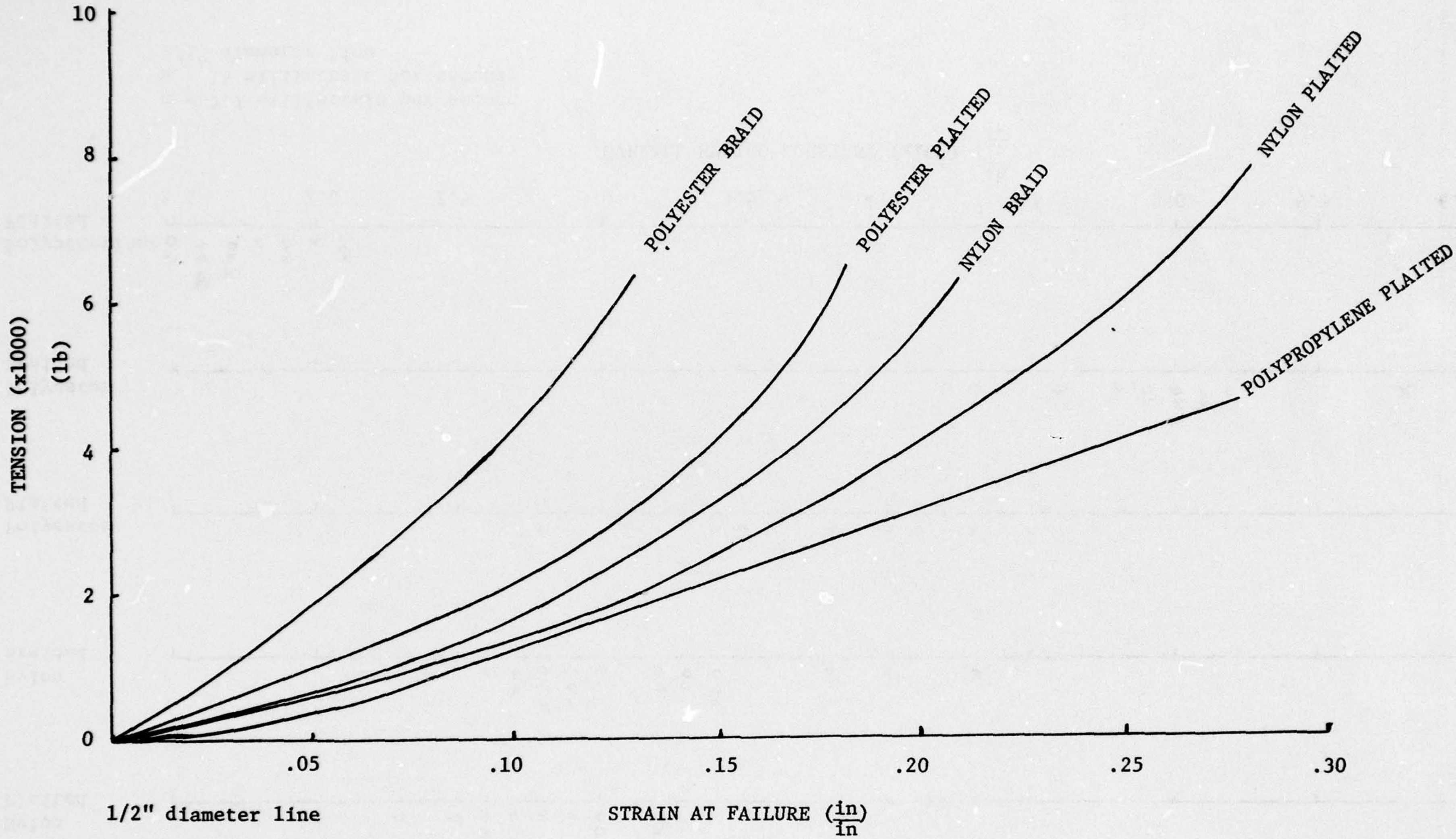



Figure 4. Tension-Strain Curves

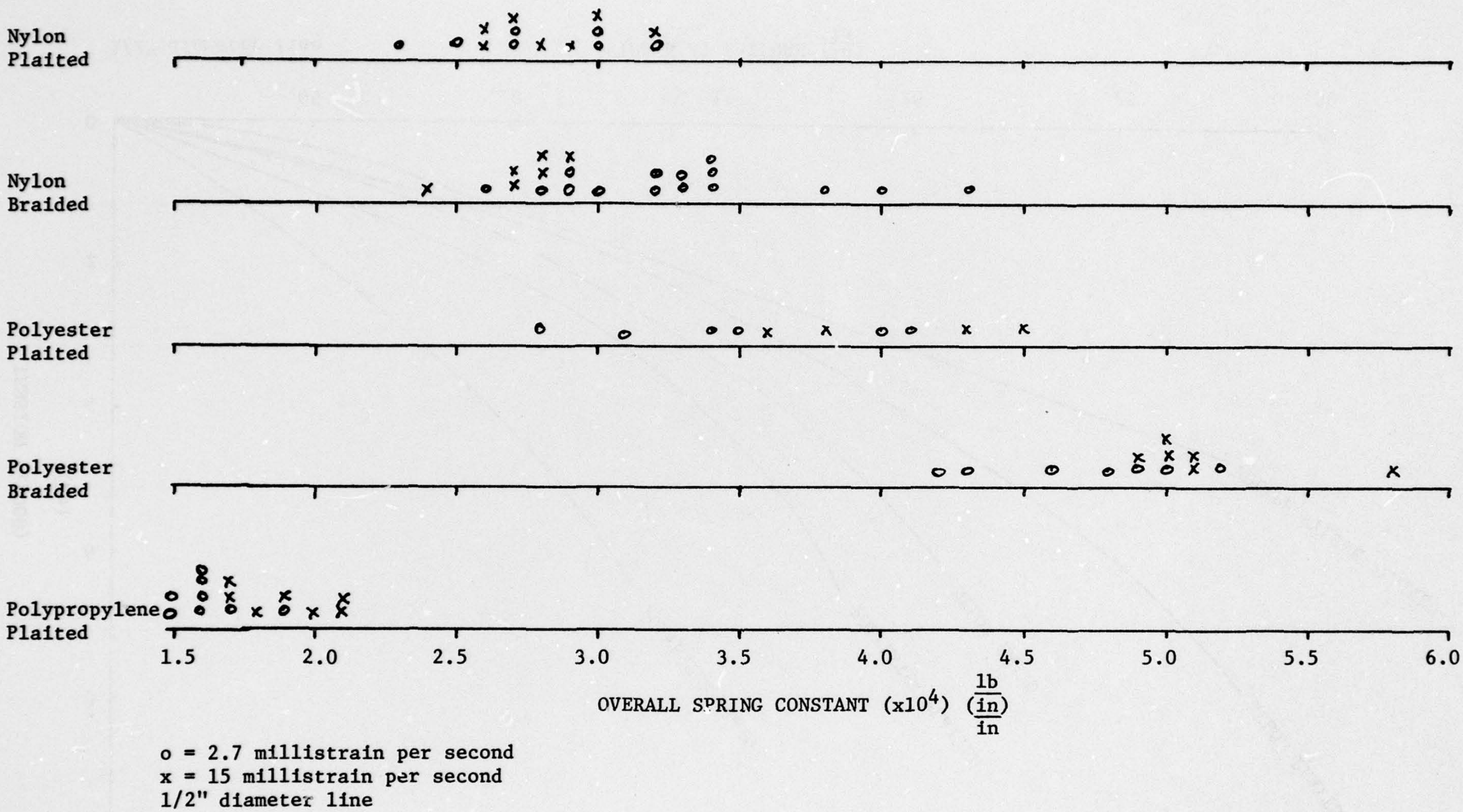



Figure 5. Histogram of Overall Spring Constant

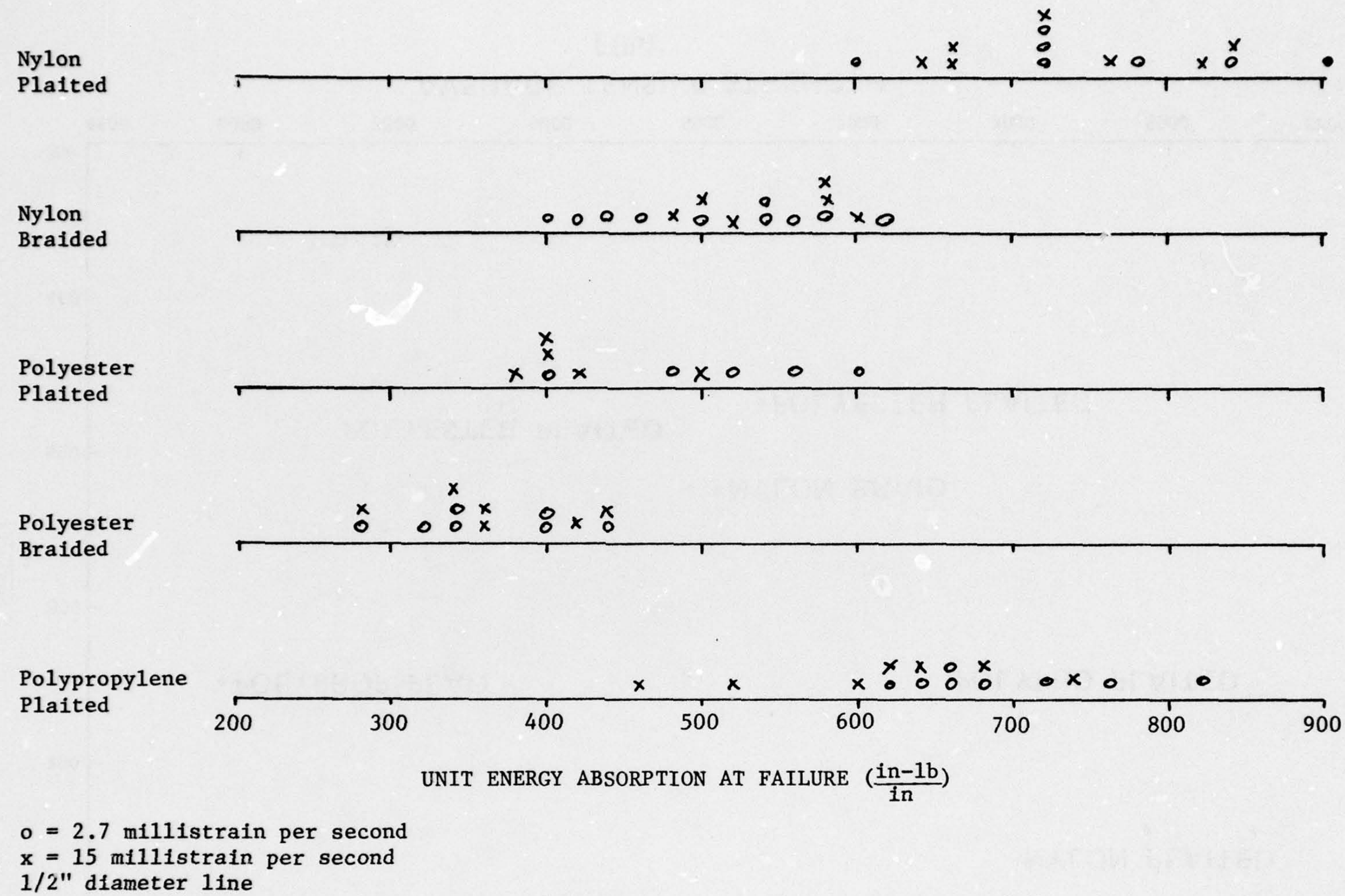



Figure 6. Histogram of Unit Energy Absorption

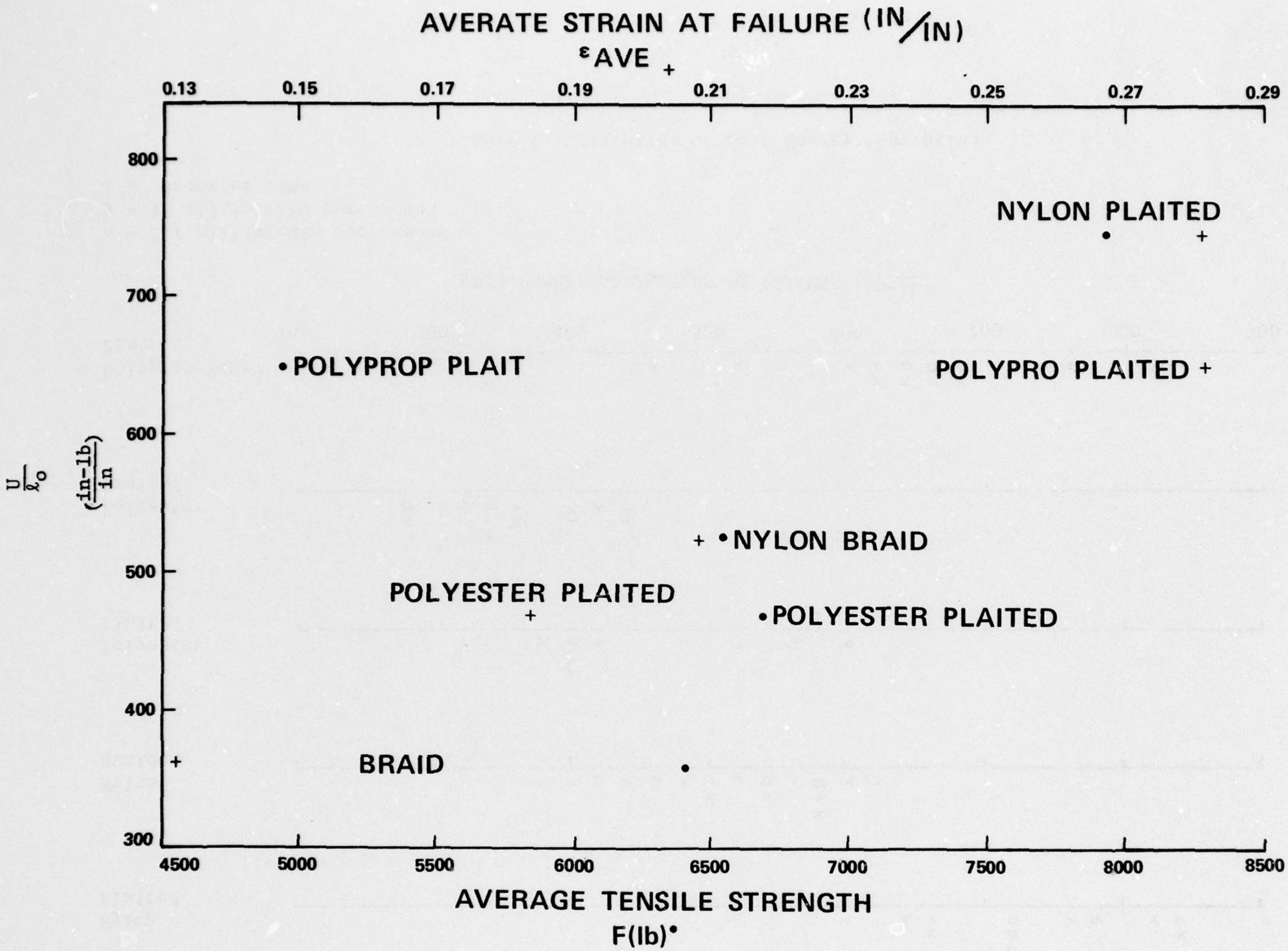
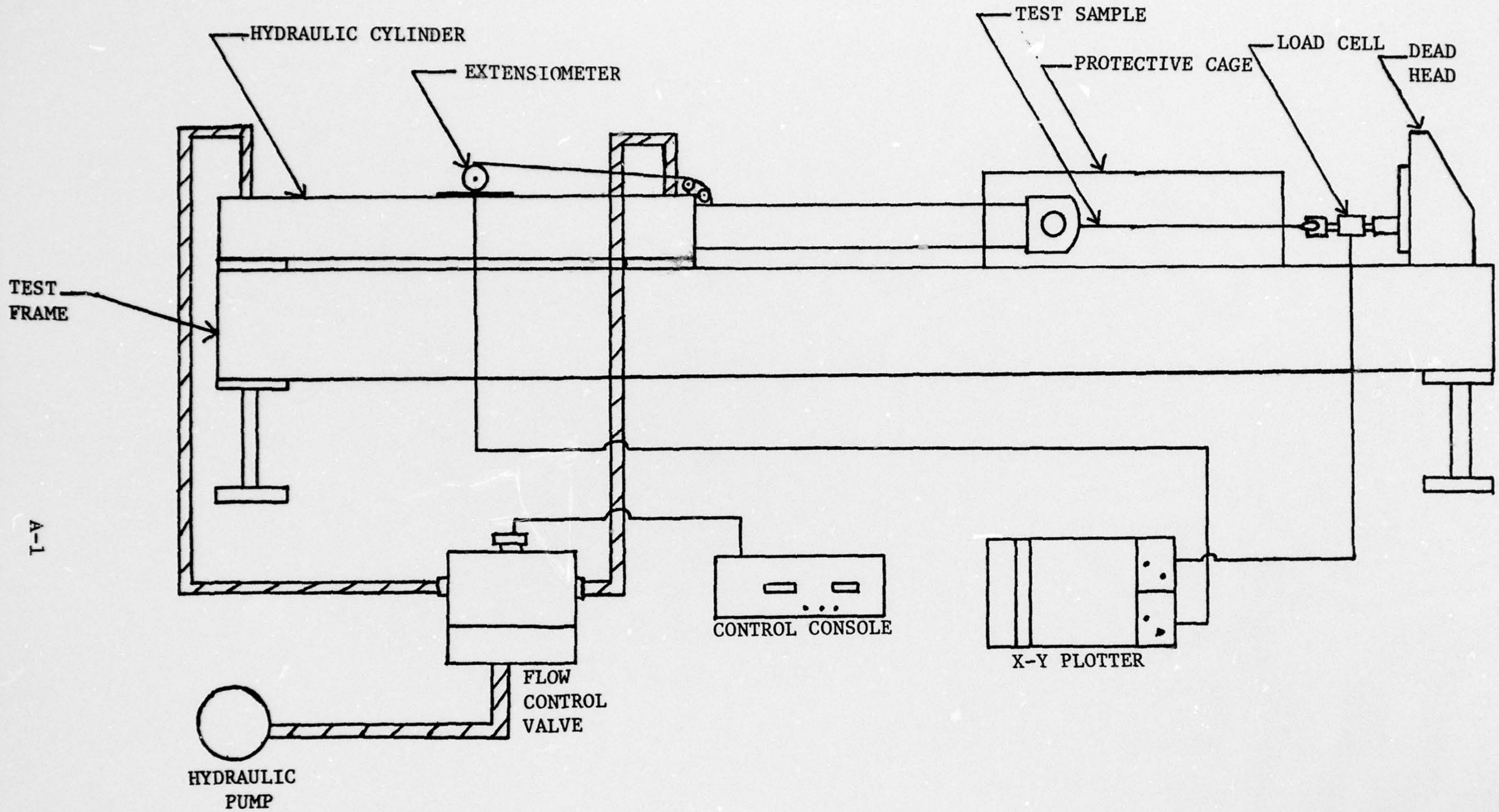
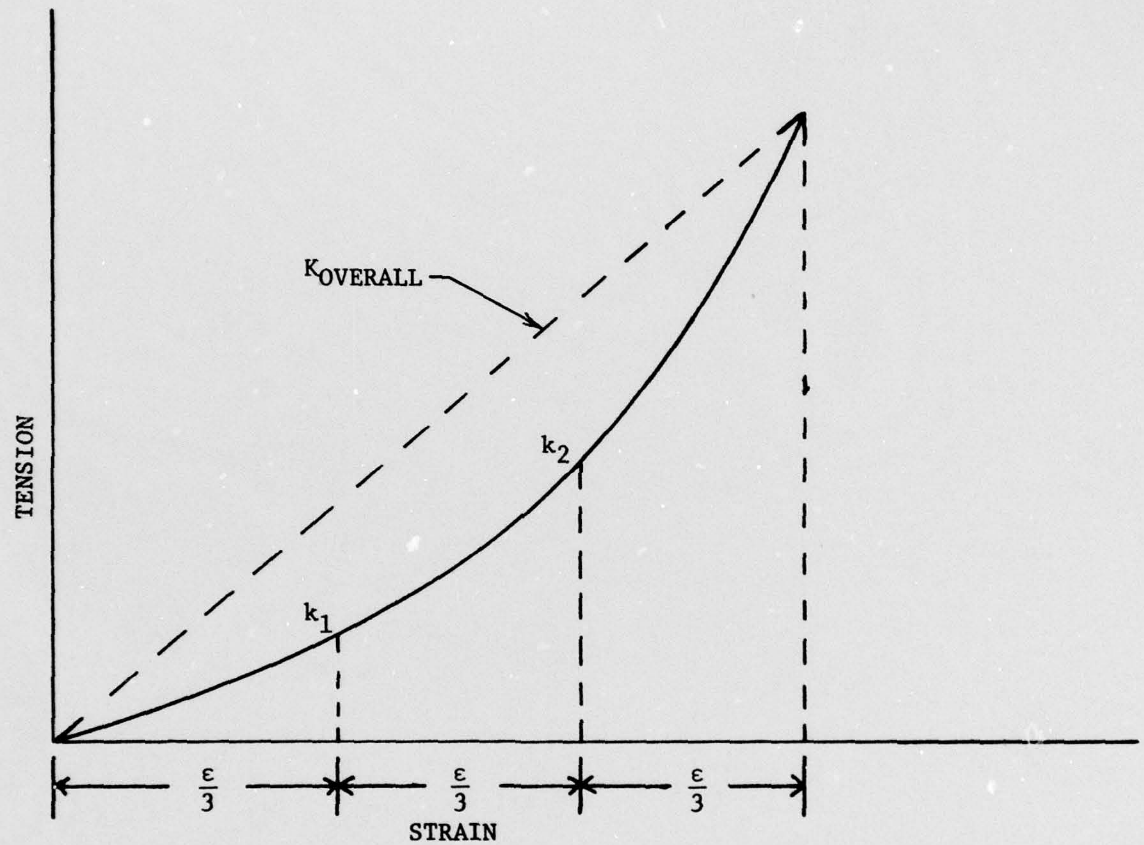



Figure 7. Energy absorption versus strain and tensile strength.




APPENDIX 1

CYCLIC/TENSILE TEST MACHINE




APPENDIX 2

SPRING CONSTANT DEFINITION

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